

# A cryogenic amplifier for fast real-time detection of single-electron tunneling

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We employ a cryogenic High Electron Mobility Transistor (HEMT) amplifier to increase the bandwidth of a charge detection setup with a quantum point contact (QPC) charge sensor. The HEMT is operating at 1K and the circuit has a bandwidth of 1 MHz. The noise contribution of the HEMT at high frequencies is only a few times higher than that of the QPC shot noise. We use this setup to monitor single-electron tunneling to and from an adjacent quantum dot and we measure fluctuations in the dot occupation as short as 400 nanoseconds, 20 times faster than in previous work.

The conventional method for studying quantum dot properties electrically is to measure electron transport through the dot [1]. An alternative approach is to measure the current through a quantum point contact (QPC) located next to the dot, which is sensitive to the charge dynamics of the quantum dot [2, 3, 4, 5, 6]. This technique is very versatile and has also been used to probe the excited state spectrum of a quantum dot [7, 8], perform single-shot read-out of electron spin states [9, 10] and observe coherent electron spin dynamics in quantum dots [11].

Until now, such a the current fluctuations through such a QPC charge sensor has always been measured using a room temperature (RT) current-to-voltage (IV-) converter. This limits the measurement bandwidth to several tens of kHz [4], because of the low-pass (LP) filter formed by the capacitance of the measurement wires to ground and the input impedance of the amplifier. However, increasing this bandwidth is crucial in order to study (real-time) fast electron and nuclear spin dynamics [12] as well as to increase the single-shot spin readout fidelity [9]. One way to increase the bandwidth is to embed the QPC in a resonant circuit and measure its damping [13], analogous to the operation of the RF-SET [14]. In theory such an "RF-QPC" allows for single-shot charge detection within a few tens of nanoseconds [15]. However, this technique requires RF-modulation and is experimentally rather involved.

Here, we explore a much simpler approach to increasing the bandwidth, which uses a HEMT operated in DC as a cryogenic pre-amplifier [16]. Compared to a RT amplifier, a cryogenic amplifier can be mounted much closer to the sample, which significantly reduces the capacitance of the measurement wire. The use of a HEMT has the additional advantage that the noise level at cryogenic temperatures is very low (especially at high frequencies), so a better charge sensitivity can be obtained.

The HEMT is connected to the right lead of the QPC, which is also connected to ground via  $R_c$  (Fig. 1(a)). A bias voltage,  $V_{sd}$ , is applied to the left lead and a current  $I_{qpc}(t)$  will flow which depends on the QPC conductance

$G_{qpc}(t)$ . The voltage over  $R_c$  is a measure for this current and is probed via the HEMT. Fluctuations of  $G_{qpc}$  result in fluctuations of  $I_{qpc}$ , denoted by  $\Delta I_{qpc}$ . These generate

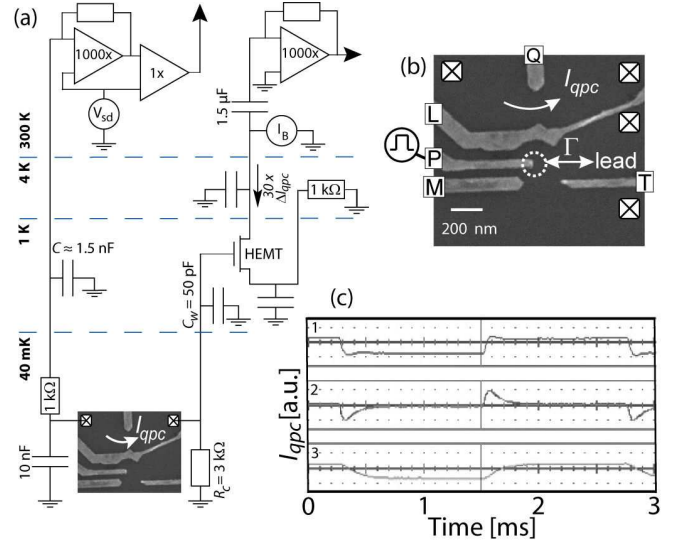


FIG. 1: (a) Schematic of the experimental setup.  $R_c$  converts fluctuations in  $I_{qpc}$  into voltage fluctuations on the HEMT gate. Through its transconductance the HEMT converts these fluctuations into current fluctuations which are amplified by an additional amplification stage at room temperature.  $R_c$  and  $C_w$  form a 1 MHz LP-filter. (b) Scanning Electron Micrograph of a similar device as used in the experiment. The dot (dashed circle) and QPC are defined in a 2DEG formed at a GaAs/AlGaAs interface 90 nm below the surface, with an electron density of  $1.3 \times 10^{15} \text{ m}^{-2}$  by applying negative voltages to gates L, M, T and Q. Fast voltage pulses can be applied to gate P. The crosses represent Ohmic contacts. (c) Response to a voltage pulse applied to gate P. Trace 1 shows the total response to a voltage pulse when  $G_{qpc} \approx \frac{e^2}{h}$ . When the QPC is pinched-off, there is still a response due to crosstalk between the pulse line and the HEMT gate-wire (trace 2), providing a measure for the bandwidth of the readout circuit from the HEMT gate up to RT ( $\sim 8 \text{ MHz}$ ). Subtracting trace 2 from 1 reveals the signal from the QPC (trace 3) with a rise time of 285 ns, corresponding to a bandwidth of 1 MHz.

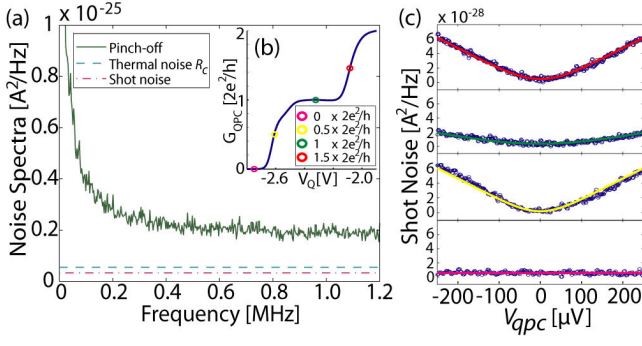


FIG. 2: (a) Noise spectrum of the setup including the cryogenic HEMT amplifier. The measured spectrum is taken for the QPC in pinch-off, thereby excluding shot noise and noise coming from the other side of the QPC. The calculated noise contributions from the QPC shot noise and the thermal noise of  $R_c$  are plotted for reference (dash-dotted and dashed line respectively). (b) QPC conductance as a function of the voltage on gate Q. (c) Measurements of the QPC shot noise power measured at the QPC conductances indicated by the colored markers in (b). Solid lines are fits to Eq. (1).

voltage fluctuations on the HEMT gate with respect to the voltage on its source,  $V_{gs}$ . The modulation of  $V_{gs}$  results in a modulation of the drain-source current,  $I_{ds}$ , through the HEMT channel. This current is measured by an AC-coupled IV-converter at RT and digitized using a digital oscilloscope (LeCroy WaveRunner 6030A).

We use a commercially available HEMT (Agilent ATF 35143) with a 400  $\mu\text{m}$  gate length and a threshold voltage  $V_t \approx 0.4$  V. When appropriately biased (by controlling  $I_B$ ), the transconductance of the HEMT is  $g_m = 10$  mA/V, which relates the drain-source current  $I_{ds}$  through the HEMT to  $V_{gs}$  as  $I_{ds} = -g_m V_{gs}$  implying  $\Delta I_{ds} \approx -30 \Delta I_{qpc}$ , using  $R_c = 3$  k $\Omega$ . The power dissipation of the HEMT is 30  $\mu\text{W}$ . In addition to the HEMT,  $I_{qpc}$  can also be measured *simultaneously* in a 100 Hz bandwidth using a IV-converter at RT which is connected to the left lead of the QPC. We refer to this measured current as the time averaged current. The quantum dot and the QPC are defined in a two-dimensional electron gas (2DEG) by applying negative voltages to metal surface gates (labeled L, M, T and Q in Fig 1(b)). Gate L completely separates the QPC source and drain electrically from the leads of the dot. The experiment is performed in a dilution refrigerator with a base temperature of 40 mK and with zero externally applied magnetic field.

First, we characterize the bandwidth of the setup. The bandwidth ( $BW$ ) is expected to be limited by the resistor  $R_c$  and the capacitance,  $C_w$ , of the measurement wire connecting the right lead of the QPC to the HEMT gate ( $BW = (2\pi R_c C_w)^{-1}$ ). The HEMT is mounted on the 1K-stage, since this has sufficient cooling power to dissipate the heat generated by the HEMT in operation. The value for  $C_w$  is then a tradeoff between two requirements:

a low capacitance and sufficient thermal anchoring of the wire. The value of  $R_c$  is also a tradeoff: increasing the value of  $R_c$  increases the amplitude of the voltage fluctuations on the HEMT gate ( $\Delta V_{gs} = \Delta I_{qpc} R_c$ ) but reduces the bandwidth of the setup (for a given value of  $C_w$ ). Our aim is to detect single-electron tunneling on a sub-microsecond timescale. The value for  $R_c$  was chosen assuming  $\Delta I_{qpc} \approx 400$  pA and an input referred voltage noise  $0.4$  nV/ $\sqrt{\text{Hz}}$ .  $R_c = 3$  k $\Omega$  then gives  $\text{SNR} \approx 3$  and a bandwidth of 1 MHz. The bandwidth is determined by measuring the QPC response to fast voltage pulses applied to gate P. The measured rise times are 285 ns, yielding a bandwidth of 1 MHz, in excellent agreement with the designed bandwidth (Fig. 1(c)).

The next step is a characterization of the noise level. We measure the total noise spectral density and plot this as an input referred current noise in Fig. 2(a). A characteristic  $1/f$  contribution is present up to 200 kHz. For frequencies above 200 kHz, the spectrum is approximately flat, saturating at  $0.2 \times 10^{-25} \text{ A}^2/\text{Hz}$  ( $= 0.4$  nV/ $\sqrt{\text{Hz}}$ ). This is very close to the voltage fluctuations generated by the QPC shot noise (calculated to be  $S_I = 0.17$  nV/ $\sqrt{\text{Hz}}$ , for 1 mV bias over the QPC [4]). We test this by a *direct* measurement of the QPC shot noise. We measure the rms voltage after band-pass filtering the output of the RT IV-converter (bandwidth from 500 kHz to 1 MHz). In Fig. 2(b) we show the QPC conductance  $G_{qpc}$  as a function of the voltage on gate Q, determined from the time averaged current. The colored markers indicate the QPC conductances ( $G_{qpc} = n \frac{e^2}{h}$ ,  $n = 0, 1, 2, 3$ ) at which the shot noise was measured as a function of bias over the QPC,  $V_{qpc}$ , see Fig. 2(c).  $V_{qpc}$  is varied by changing  $V_{sd}$ . We verified that the QPC was in its linear regime for the entire range of  $V_{qpc}$ . The shot noise spectral density  $S_I$  can be expressed as [17, 18]

$$S_I = \frac{2e^2}{h} \sum_i \mathcal{N}_i \left[ eV_{qpc} \coth \left( \frac{eV_{qpc}}{2k_B T_e} \right) - 2k_B T_e \right] \quad (1)$$

where  $\mathcal{N}_i = T_i(1 - T_i)$  with  $T_i$  the QPC transmission coefficient of mode  $i$ ,  $V_{qpc}$  the bias over the QPC,  $k_B$  the Boltzmann constant and  $T_e$  the electron temperature. The solid lines in Fig. 2(c) are fits to Eq. (1) yielding  $\mathcal{N} = 0.234, 0.090, 0.229$  and 0 from top to bottom, in agreement with the QPC conductances. The measurements prove that the input referred voltage noise is indeed very close to the shot noise limit in this setup. From the fits we also extract the electron temperature  $T_e = 255$  mK, consistent with the value obtained from the width of Coulomb peaks ( $T_e = 267$  mK).

The noise measurements show that the noise from the HEMT is in agreement with our initial estimation. We therefore expect to have sufficient SNR to detect single-electron tunnel events. To test this experimentally, the dot is tuned to be near the  $0 \leftrightarrow 1$  electron transition by adjusting the voltages on gates L, M and T, and to be

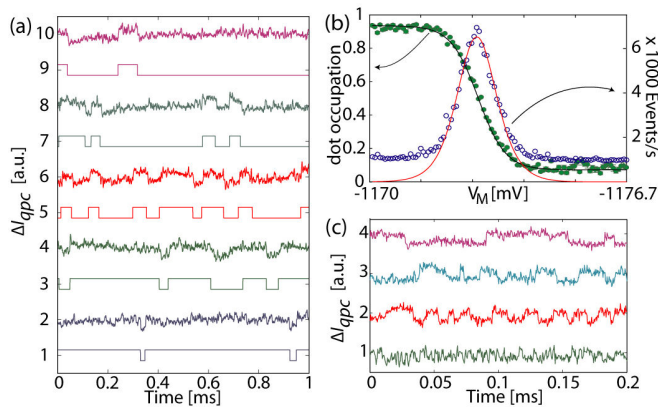


FIG. 3: (a) Measured QPC current when increasing the dot potential from top to bottom. The result of our flank detection routine is plotted below each measured trace. An additional band-pass filter (200 Hz - 200 kHz) was used for this measurement. (b) Dot occupation extracted from the same data as (a) as a function of  $V_M$ . From the same data we extract the number of tunnel events per second as a function of  $V_M$  from which we can extract the tunnel rate [20]. The solid curves are fits to the data (see text). (c) The tunnel rate  $\Gamma$  is increased from top to bottom by decreasing the negative voltage on gate T. Here, the signal was band-pass filtered from 3 kHz to 1 MHz. The shortest detectable events are on the order of 400 ns.

isolated from the bottom lead [7]. The dot remains coupled to the other lead with a tunable tunnel rate,  $\Gamma$ . An electron is now allowed to tunnel back and forth between the dot and the lead and the QPC current should therefore exhibit a random telegraph signal (RTS). The QPC conductance is set again at approximately  $\frac{e^2}{h}$ . In order to maximize  $\Delta I_{qpc}$ , we want to apply the highest possible bias,  $V_{qpc}$ . However, for  $V_{qpc} > 0.65$  mV, we observe a severe change in the dot occupation, most probably due to intradot excitations to the first orbital excited state [19]. We therefore restrict ourselves to QPC bias voltages below 0.65 mV. This reduces  $\Delta I_{qpc}$  to 320 pA, resulting in a lower SNR. Measurements of the RTS are shown in Fig. 3. To verify that the measured RTS originates from electron tunnel events between the dot and the lead, we varied two control parameters, as in [4]: (1) the dot electrochemical potential  $\mu$  relative to the Fermi level of the lead  $\mu_F$  and (2) the tunnel barrier between the dot and the lead. The dot potential is changed by changing the voltage on gate M. The dot occupation probability  $P$  depends on  $\mu - \mu_F$  and the temperature broadening of the lead so it should directly reflect the Fermi-Dirac distribution of electronic states in the lead. We infer the dot occupation from the measured average time the electron spends on (off) the dot,  $\tau_{on(off)}$ , as  $P = \frac{\tau_{off}}{\tau_{on} + \tau_{off}}$ , [5]. However, since both the HEMT and the RT IV-converter AC-coupled, signals from the QPC are high-pass filtered (1.2 kHz cut-off). We can therefore not use a simple threshold detection scheme [9] but instead de-

tect the flanks of the steps in  $\Delta I_{qpc}$  to obtain the single-electron tunneling statistics. In Fig. 3(b) the average dot occupation is plotted versus the voltage on gate M ( $V_M$ ). At  $V_M = -1172.8$  mV,  $\mu$  is aligned with  $\mu_F$ . The solid black line is a fit to the Fermi-Dirac distribution function  $f(\mu)$  yielding an electron temperature  $T_e = 275$  mK. The average times  $\tau_{on/off}$  also allow the determination of the tunnel rate  $\Gamma$ . The Fermi distribution and the tunnel rate  $\Gamma$  determine the average number of tunnel events per second as  $r_e = 1/(\tau_{on} + \tau_{off}) = \Gamma \times f(\mu) [1 - f(\mu)]$ . This is also plotted in Fig. 3(b). The fit to this data yields  $\Gamma = 26.1$  kHz (solid red line) [20]. The tunnel rate  $\Gamma$  can be varied via the voltage on gate T (Fig. 3(c)). The shortest detectable events are on the order of 400 ns. The charge sensitivity reached is  $4.4 \times 10^{-4} e/\sqrt{\text{Hz}}$  in the range 200 kHz - 1 MHz, only 3.8 times larger than the shot noise limit in this setup with  $V_{qpc} = 0.65$  mV.

We have demonstrated that a HEMT can be used as a cryogenic amplifier to increase the measurement bandwidth of a QPC charge detection setup. The bandwidth of the setup is 1 MHz and the input referred voltage noise is measured to be  $0.4$  nV/ $\sqrt{\text{Hz}}$  above  $\sim 200$  kHz, which is close to the QPC shot noise limit. This allows us to detect fluctuations in the dot occupation as short as 400 ns, 20 times faster than previously achieved using a QPC as a charge sensor. The bandwidth could be further increased by placing the HEMT even closer to the sample (since the dissipation in the HEMT is low enough), which would reduce the capacitance even more. A lower amplifier noise (both  $1/f$  and baseline) could be obtained by using a HEMT with a larger gate area.

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  - [20] For every trace without a tunnel event, the total length of the trace (1 ms) is assigned to  $\tau_{on/off}$ . This results in a baseline of 1000 events/s instead of 0. To determine  $\Gamma$ , we fit to a subset of the data with a sufficient number of tunnel events.